Oceans in Europa and Callisto: Independent Evidence from Magnetic Perturbations

(Original title: Further evidence for the presence of oceans in Europa and Callisto)

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Galileo, the first artificial satellite of an outer planet, has been orbiting Jupiter since Dec 7, 1995. The spacecraft encounters one of the four Galilean satellites on each orbit. Among the principal results from the magnetometer are the discoveries of an internal magnetic field in Ganymede[1] and a possible internal magnetic field in Io[2]. Through late March 1998, Galileo also encountered Europa at close range (altitude < 1 R_E ≡ radius of Europa, 1560 km) five times and Callisto (altitude < 0.5 R_C ≡ radius of Callisto, 2409 km) three times. Initial publications[3,4] reported that neither Europa nor Callisto has an appreciable internal field (comparable to that of

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Ganymede). This communication presents evidence that the perturbations recorded during the encounters arise from induced magnetic fields. Induction requires current to flow within the moon in response to time variations of the externally imposed magnetic field. Thus there must be layers of significant electrical conductivity near the surfaces of both of these moons, a requirement that constrains models of the interiors of these bodies.

Our new insight into the source of the magnetic perturbations recorded near the moons is based on data from four passes for which the signal (induction signature) to noise (perturbations generated within the ambient magnetospheric plasma) ratio is large. Further details of the results from these and other Europa and Callisto flybys will appear elsewhere (Kivelson, M. G., et al., Europa and Callisto: Induced or intrinsic fields in a periodically varying plasma environment, *J. Geophys. Res.*, to be submitted, 1998). Europa and Callisto are located in the inner magnetosphere of Jupiter where the plasma is confined to a thin sheet (half thickness ~ 2 R_J) near the dipole equator. Jupiter's strong magnetic field keeps the ambient plasma close to rigid corotation with Jupiter, implying that it overtakes the orbiting moons from behind. In the rest frame of the moons, the magnetospheric field wobbles as shown in Figure 1. A varying magnetic field with a peak amplitude of ~ 220 nT (~40 nT) is imposed on Europa (Callisto) at the synodic period of Jupiter's rotation. Conductors within or surrounding the moons respond to such varying fields by generating eddy currents on their surfaces. In a uniform oscillating field, eddy currents on the surface of a highly conducting sphere or a spherical shell generate the field of an oscillating magnetic dipole external to the conductor and cancel the oscillating field inside the conductor[5]. Continuity of the normal component of the

magnetic field requires that at the pole of the induced dipole, the induced field cancel the background field.

The interactions of the moons with the magnetospheric plasma perturb the background field complicating the interpretation of the induction signature. At Europa, the principal plasma effect comes from the mass loading of the plasma from newly picked up water group ions. Such an interaction enhances the field strength upstream of the moon and decreases it downstream of the moon. Other plasma related effects that obscure the induction signature include the standing Alfvén wave current system that flows through an external conducting layer[6] surrounding the moon (an ionosphere, for example), diamagnetism from newly picked-up plasma, an expansion fan introduced in the wake of a non-conducting moon by the absorption of plasma by the moon[7], and the ambient ultra-low frequency (ULF) waves present in the plasma sheet of Jupiter[8]. To minimize the complications arising from the plasma effects we have concentrated on two of the Europa flybys (orbits E4 and E14) and two of the Callisto flybys (orbits C3 and C9) for which the moons were located outside of the central dense part of Jupiter's plasma sheet. For these passes, the moon-plasma interaction was weak and the background fluctuations from ULF waves were small.

Figure 2 shows data from encounter E14. (See Figure 1 for parameters of this and other encounters.) Also plotted are the predictions from the induction model (with no adjustable parameters). Near the equatorial plane of Europa, where these observations were made, induction is not expected to modify B_z greatly. We believe that the field magnitude and B_z are enhanced during this and other Europa encounters principally by mass loading[9], diversion of flow by the conducting obstacle and associated plasma

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effects. As the component of **B** along the flow direction is small ($B_x/|B| \ll 1$) for all the encounters, plasma effects will be symmetric about a plane through the center of the moon perpendicular to the background magnetic field. Above and below this plane, plasma currents drape the field around the moon, causing bending. In the symmetry plane, near which these observations were made, plasma effects change the field strength without changing its orientation. If the orientation of the field is not to change, each component must change by the same fractional amount: $\delta B_x / B_x \cong \delta B_y / B_y \cong \delta B_z / B_z \cong \delta|B|/|B|$. Here $\delta|B|$ is the change in the field strength. Thus, by reducing each component by a factor $(1 - \delta|B|/|B|)$, we can approximately remove the plasma contributions. The correction improves the agreement between the observations and the model for both the E14 and E4 flybys.

At Callisto, corrections for plasma effects are not needed. Figure 3 shows the observed perturbations and the induced dipole model for the C3 and C9 passes and agreement is good. As these Callisto encounters occurred at opposite phases of the variation of the background field (away from Jupiter for the C3 flyby and towards Jupiter for C9), the induced dipole moments were roughly antiparallel (see Figures 3a and 3b). This convincingly demonstrates that the Callisto observations cannot be explained by a fixed internal dipole. For the multiple Europa observations, the orientation of the time-varying component of Jupiter's field changed only slightly among the relevant passes, so the induced dipole moments differed only slightly. A fixed internal dipole cannot be excluded, although its orientation at a large angle to the spin axis seems improbable.

The induced field model for Europa and Callisto constrains their interior structures by requiring conducting paths at or near the surfaces. It is well known that a periodically

varying magnetic field (angular frequency ω) acting on an electrically conducting object of conductivity σ decays in an e-folding length of $S = (\omega\mu\sigma / 2)^{-1/2}$. Here S is the skin depth and μ is the permeability. If the period of the wave is 11 hours and the conductivity is 1 S/m, $S \approx 95$ km. The solution for a spherical shell can be expressed in terms of Bessel functions, but when the thickness of the conducting layer is $\geq 0.1\ S$ and $S \ll a$ with a the radius of the conductor, the solution outside the conductor is the sum of an induced dipole field and the uniform background field[5] (see Figure 2 legend).

The observed amplitudes of the induced signatures of Europa and Callisto require conducting layers of depth $> 0.1\ S$ near their surfaces. For Europa, an obvious candidate for conducting paths is its ionosphere[10] or a cloud of pickup ions[11]. However, estimates of the conductivity above the surface give skin depths for a ten-hour wave much larger than the moon itself. Thus, the wave easily penetrates the ionosphere without causing significant induction. Skin depths (for an approximately ten-hour wave) of various materials likely to be found in the icy outer layers of Europa or Callisto can be determined. A rocky mantle composed of (pure) ice and rocks would have a skin depth greater than 10^6 km. Metals such as iron are not expected to be abundant in the outer layers of a differentiated body. Induction from inner metallic cores can also be ruled out. A metallic core whose radius is half the moon's radius would produce a signature that is only one eighth as large as observed because the induced dipole field magnitude falls as inverse distance cubed. An ocean whose salinity is comparable with Earth's ocean could produce the signature. The conductivity of Earth's ocean water[12] (salinity 3.75%) is ~ 2.75 S/m at 0° C. Thus, Earth-like oceans with thicknesses >10 km could generate the observed signatures in Europa and Callisto. The conductivity of ocean water is

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electrolytic and requires only small amounts (a few percent) of dissolved salts (like NaCl) or acids (like H_2SO_4) that hydrolyze readily.

Induced fields at Europa have been considered since 1985[13], followed by more recent speculations[14]. Neubauer[11] noted that the published[3,4] dipole moments of the magnetic field perturbations near Europa and Callisto can be fully or partially explained by induction from subsurface oceans or a dirty ice layers near the melting point.

The possibility of a liquid water ocean beneath the icy surface of Europa has been debated for more than two decades. Accretional and radiogenic heat sources are large enough to dehydrate the interior of Europa early in its evolution leaving the satellite covered with a layer of liquid water 100 km or more thick[15]. Galileo measurements of Europa's gravitational field show that Europa is strongly differentiated (with a metallic core) and that it indeed has a water ice-liquid outer layer about 100 km thick[16].

Early thermal models considered only the conductive cooling and freezing with time of the outer layer of water and were left at present with liquid water beneath an ice shell. It was later shown[17] that with thickening, the outer layer of ice would become unstable to thermal convection, promoting heat transfer through the ice and solidification of the underlying water. Complete freezing of the outer layer of water in a small fraction of geologic time is possible but not certain[18], even for pure water. Additionally, tidal dissipation in Europa's ice shell provides a heat source that could offset the convective cooling of the ice and prevent complete solidification of the water ocean[19].

The competition between the tendency of tidal heating to maintain a liquid water ocean and that of ice convection to freeze the ocean has been analyzed without benefit of a definitive conclusion[20,21,22]. Major uncertainties include the unknown rheology of ice[23]

and the dependence of ice thermal conductivity on its temperature and physical state. A thermally insulating surface layer would promote stabilization of a liquid water ocean[21]. The occurrence of minor constituents in the ice and ocean such as salts[24] and ammonia would affect the rheology of the ice and the freezing temperature of the ocean. Tidal heating on major faults in the ice[25] and frictional dissipation due to forced circulation in a thin liquid water ocean may be important.

While the possible existence of a liquid water ocean on Europa is plausible, the opposite is true for Callisto. Callisto consists of roughly equal amounts of rock and ice. It is not tidally heated and there is no geologic evidence for significant endogenic modification of its surface. Galileo gravity measurements show only partial separation of the ice and rock in Callisto's interior[26]. Observations are consistent with little modification of Callisto since its accretion. Thermal models of Callisto give no hint of a subsurface liquid water ocean[15]. Accretional and radiogenic heating are marginally able to separate the ice and rock inside Callisto, but the present gravitational evidence shows that unlike Ganymede[27] separation has been incomplete. Callisto has not been heated enough to have melted all its ice.

The question remains if some of the ice in the outer part of Callisto has melted and if a near surface liquid water layer could be prevented from freezing. Since accretional heating is largest when a planet is near maximum size it is possible for the ice to have melted in the outer layers of Callisto. More problematic is keeping such a layer from freezing; tidal heating is necessary for the maintenance of a liquid ocean on Europa and there is no tidal heating on Callisto. The presence of antifreeze (salts or ammonia) would help. The layer needs to have substantial thickness and for this reason an ocean

separating two solid convecting regions is most plausible. The possibility of a liquid water ocean in Callisto is startling but we have no other explanation for the near surface highly electrically conducting layer required by the observed induction signal. Of the two icy Galilean satellites, it would be more plausible for Ganymede to have a subsurface liquid water ocean. Ganymede is completely differentiated and extensive endogenic modification of its surface and the existence of an intrinsic magnetic field[1] imply a dynamic interior in the past and even to the present[28]. Perhaps Ganymede also has an internal liquid water ocean if Callisto has one, but Ganymede's intrinsic magnetic field obscures any induction signal.

How significant is the ohmic heating from the eddy currents in the moons? The dissipated power can be estimated from the expression[29]: Power/area = $S\omega B^2 / 4\mu_o$, the ohmic loss from a propagating electromagnetic wave in a conducting waveguide. Multiplication by the surface area of the moon and substitution of varying field amplitudes of 220 nT (Europa) and 40 nT (Callisto) gives 5×10^6 (S/100 km) W for Europa and 4×10^5 (S/100 km) W for Callisto. Nominal values for S are of order 100 km. More rigorous estimates would not change the conclusion that the heat input from this source is negligible.

In summary, from an analysis of the magnetic field observations we conclude it is very likely that both Europa and Callisto possess internal salty liquid water oceans. In the case of Europa, this conclusion is supported by indirect geologic evidence[30,31].

[1] Kivelson, M. G., Khurana, K.K., Russell, C. T., Walker, R. J., Warnecke, J., Coroniti, F.V., Polanskey, C., Southwood, D. J., Schubert, G., Discovery of Ganymede's magnetic field by the Galileo spacecraft, *Nature,* **384**, 537 (1996).

[2] Kivelson, M. G., Khurana, K. K., Walker, R. J., Russell, C. T., Linker, J. A., Southwood, D. J., Polanskey, C., A magnetic signature at Io: Initial report from the Galileo magnetometer, *Science,* **273**, 337-340 (1996).

[3] Kivelson, M. G., K. K. Khurana, S. Joy, C. T. Russell, R. J. Walker, and C. Polanskey, Europa's magnetic signature: Report from Galileo's first pass on December 19, 1996, *Science,* **276**, 1239 (1997).

[4] Khurana, K. K., M. G. Kivelson, C. T. Russell, R. J. Walker, and D. J. Southwood, Absence of an internal magnetic field at Callisto, *Nature,* **387**, 262 (1997).

[5] Parkinson, W. D, *Introduction to Geomagnetism,* p. 308-340, Scottish Academic Press Ltd., Edinburgh, U. K (1993).

[6] Neubauer, F. M., Nonlinear standing Alfvén wave current system at Io: Theory, *J. Geophys. Res.,* **85**, 1171 (1980).

[7] Owen, C. J., et al., The lunar wake at 6.8 R_L: WIND magnetic field observations, *Geophys. Res. Lett.,* **23**, 1263 (1996).

[8] Khurana K. K., and M. G. Kivelson, Ultra low frequency MHD waves in Jupiter's middle magnetosphere, *J. Geophys. Res.,* **94**, 5241 (1989).

[9] Ip, W.-H., Europa's oxygen exosphere and its magnetospheric interaction, *Icarus,* **120**, 317 (1996).

[10] Kliore, A. J., D. P. Hinson, F. M. Flasar, A. F. Nagy, and T. E. Cravens, The ionosphere of Europa from Galileo radio occultations, *Science,* **277**, 355 (1997).

[11] Neubauer, F. M., The subalfvénic interaction of the Galilean satellites with the Jovian magnetosphere, *J. Geophys. Res. (planets)* in press (1997).

[12] Montgomery, R. B., Oceanographic data, In *American Institute of Physics Handbook,* pp. 125-127, McGraw Hill, New York (1963)

[13] Colburn, D.S. and R. T. Reynolds, Electrolytic currents in Europa, *Icarus,* **63**, 39 (1985).

[14] Kargel, J. S., and G. J. Consolmagno, Magnetic fields and the detectability of brine oceans in Jupiter's icy satellites, *Lun. Planet. Sci. Conf.,* **XXVII**, 643-644 (1996).

[15] Schubert, G., T. Spohn, and R. Reynolds, Thermal histories, compositions and internal structures of the moons of the solar system, in *Satellites,* J. A. Burns and M. S. Matthews, eds., University of Arizona Press, Tucson, Arizona, 224–292 (1986).

[16] Anderson, J. D., G. Schubert, R. L. Jacobsen, E. L. Lau, W. B. Moore, and W. L. Sjogren, Europa's differentiated internal structure: Inferences from four Galileo encounters, *Science,* in press (1998).

[17] Reynolds, R. T. and P. Cassen, On the internal structure of the major satellites of the outer planets, *Geophys. Res. Lett.,* **6**, 121-124 (1979).

[18] Kirk, R. L. and D. J. Stevenson, Thermal evolution of a differentiated Ganymede and implications for surface features, *Icarus,* **69**, 91-135 (1987).

[19] Cassen, P. M., R. T. Reynolds, and S. J. Peale, Is there liquid water on Europa ?, *Geophys. Res. Lett.,* **6**, 731-734 (1979).

[20] Squyres, S. W., R. T. Reynolds, P. M. Cassen, and S. J. Peale, Liquid water and active resurfacing on Europa, *Nature*, **301** 225-226 (1983).

[21] Ross, M. N., and G. Schubert, Tidal heating in an internal ocean model of Europa, *Nature*, **325** 133-134 (1987).

[22] Ojakangas, G. W., and D. L. Stevenson, Thermal state of an ice shell on Europa, *Icarus*, **81**, 220-241 (1989).

[23] Durham, W.B., S. H. Kirby, and L. A. Stern, Creep of water ices at planetary conditions: A compilation, *J. Geophys. Res.*, **102**, 16,293-16,302 (1997).

[24] McCord, T. B., G. B. Hansen, F. P. Fanale, R. W. Carlson, D. L. Matson, T. V. Johnson, W. D. Smythe, J. K. Crowley, P. D. Martin, A. Ocampo, C. A. Hibbitts, J. C. Granahan, and the NIMS Team, Salts on Europa's surface detected by Galileo's Near Infrared Mapping Spectrometer, *Science*, **280**, 1242 (1998).

[25] Stevenson, D. J., Heterogeneous tidal deformation and geysers on Europa, *Europa Ocean Conference*, San Juan Capistrano Research Institute, San Juan Capistrano, California, November 12-14 (1996).

[26] Anderson, J. D., G. Schubert, R. A. Jacobsen, E. L. Lau, W. B. Moore, and W. L. Sjogren, Distribution of rock, metals, and ices in Callisto, *Science*, **280**, 1573-1576 (1998).

[27] Anderson, J. D., E. L. Lau, W. L. Sjogren, G. Schubert, and W. B. Moore, Gravitational constraints on the internal structure of Ganymede, *Nature*, **384**, 541-543 (1996).

[28] Schubert, G., K. Zhang, M. G. Kivelson, J. D. Anderson, The magnetic field and internal structure of Ganymede, *Nature* , **384**, 544-545 (1996).

[29] Jackson, J. D., *Classical Electrodynamics, second edition,* (equation 8.12), J. Wiley and Sons, N. Y., 1975

[30] Carr, M. H., M. J. S. Belton, C. R. Chapman, M. E. Davies, P. Geissler, R. Greenberg, A. S. McEwen, B. R. Tufts, R. Greeley, R. Sullivan, J. W. Head, R. T. Pappalardo, K. Klassen, T. V. Johnson, J. Kaufman, D. Senske, J. Moore, G. Neukum, G. Schubert, J. A. Burns, P. Thomas, and J. Veverka, Evidence for a subsurface ocean on Europa, *Nature*, **391**, 363-365 (1998).

[31] Pappalardo, R. T., J.W. Head, R. Greeley, R. J. Sullivan, C. Pilcher, G. Schubert, W. B. Moore, M. H. Carr, J. M. Moore, M. J. S. Belton, and D. L. Goldsby, Geological evidence for solid-state convection in Europa's ice shell, *Nature*, **391**, 365-368 (1998).

Figure Captions

Figure 1. Near the orbits of the satellites (Europa and Callisto orbits lie nearly in Jupiter's spin equator at 9.4 R_J and 26.3 R_J, respectively) but remote from the actual satellite locations, the sources of magnetic field are the internal tilted dipole of Jupiter and the currents flowing in the magnetospheric plasma sheet. The 9.6° tilt between Jupiter's spin and dipole axes implies that the magnetic equatorial plane and the orbital planes of the moons are inclined relative to each other. In a coordinate system with the x-axis along the direction of plasma corotation, the y-axis oriented towards Jupiter, and the z-axis along the spin axis of the moon, the z component remains essentially constant. However,

the x and y components of the magnetospheric field vary at the synodic period of Jupiter's rotation (11.1 hours for Europa and 10.1 hours for Callisto) as illustrated in the plots. (a) The elliptically-polarized variation of the magnetic field at Europa. Open circles mark the field values corresponding to the E4 and E14 flybys. (b) The almost linearly polarized variation of the magnetic field at Callisto. Open circles mark the field values corresponding to the C3 and C9 flybys. The time, altitude, and latitude relative to the moon's equator for the four passes were: E4: 1996-Dec-19 06:52:58 UT, 688.1 km, −1.6°; E14: 1998-Mar-29 13:21:16 UT, 1641.3 km, 12.0°; C3: 1996-Nov-04 13:34:28 UT, 1138.9 km, 13.2°; C9: 1997-Jun-25 13:47:50 UT, 421.0 km, 2.0°. At the times of these encounters, the SIII west longitude and position relative to the Jovian plasma sheet were: E4: 156.8°; ~1 R_J above; E14: 184.4°, ~1 R_J above; C3: 242.9°, ~1 R_J above; C9: 59.9°, ~1 R_J below with $R_J \equiv$ radius of Jupiter = 71,492 km. The expected background field was calculated from an empirical model of Jupiter's magnetospheric field that uses spherical harmonics of order 3 to describe the internal field[32] and an Euler potential formulation[33] to describe the external field from the current sheet.

Figure 2. Magnetic field observations from the E14 pass. The plot covers an interval during which the spacecraft moved inward from an initial range of 13 R_E to ~ 2 R_E at closest approach and traveled back out to a distance of 5 R_E from Europa during the 70 minute interval plotted. The observed magnetic field components and magnitude are plotted as thick solid lines. The thin solid lines represent the estimated background field of Jupiter's magnetosphere along Galileo's trajectory estimated from the interpolation of magnetic data obtained along the trajectory when the spacecraft was sufficiently far from
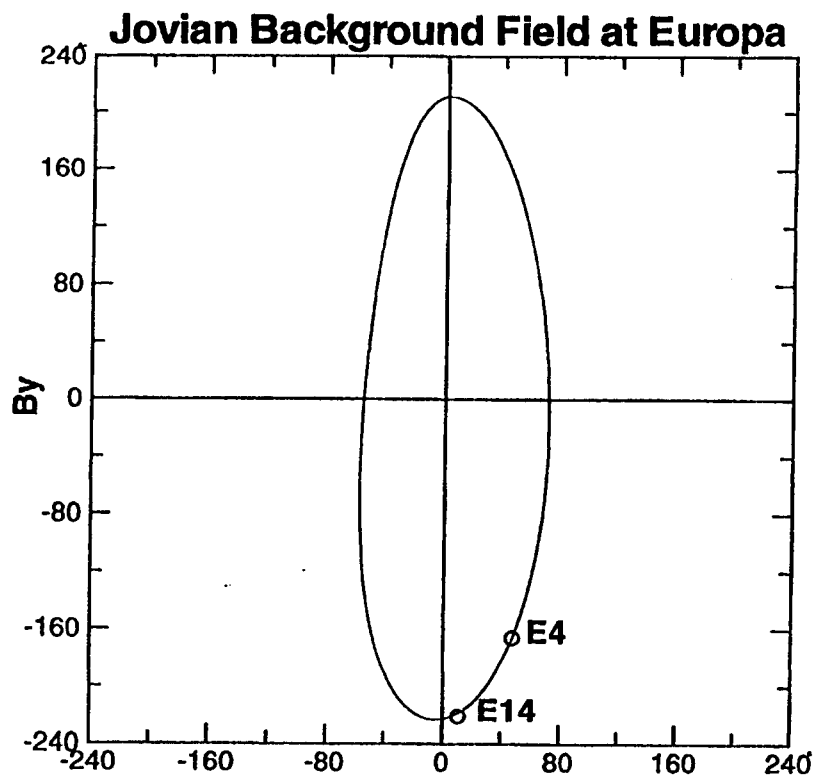
Europa (> 12 R_E) that the induction and plasma interaction effects were negligible. The modeled field (induction + background) is shown by dotted lines and provides a satisfactory fit to the large-scale field variations. Filled circles show the observations corrected for the plasma pick-up effect described in the text and this correction is seen to improve the agreement. The data sampling rate changes from 25 s to 1 s at 13:05:40 UT. The induced model field used here and in Figure 3 was calculated using the equations

$$B_r = B_o(t)\left(1 - (a/r)^3\right)\cos\theta, \quad B_\theta = B_o(t)\left(1 + 0.5(a/r)^3\right)\sin\theta, \quad B_\varphi = 0$$
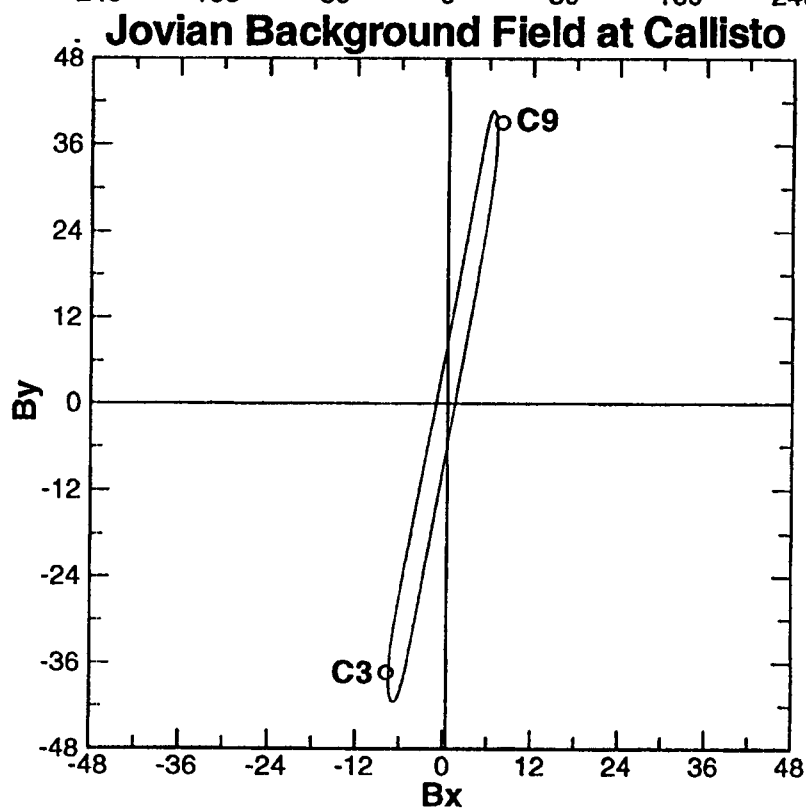
Figure 3. (a) The magnetic field perturbations (vectors drawn with solid lines) and the modeled induction field (dotted vectors) along the trajectory of the C3 encounter in the x-y plane. (b) The magnetic field perturbations and the modeled induction field for the C9 encounter.

[32] Connerney, J. E. P, Magnetic fields of the outer planets, *J. Geophys. Res.,* **98,** 18659 (1993).

[33] Khurana, K. K., Euler potential models of Jupiter's magnetospheric field, *J. Geophys. Res.,* **102,** 11295 (1997).
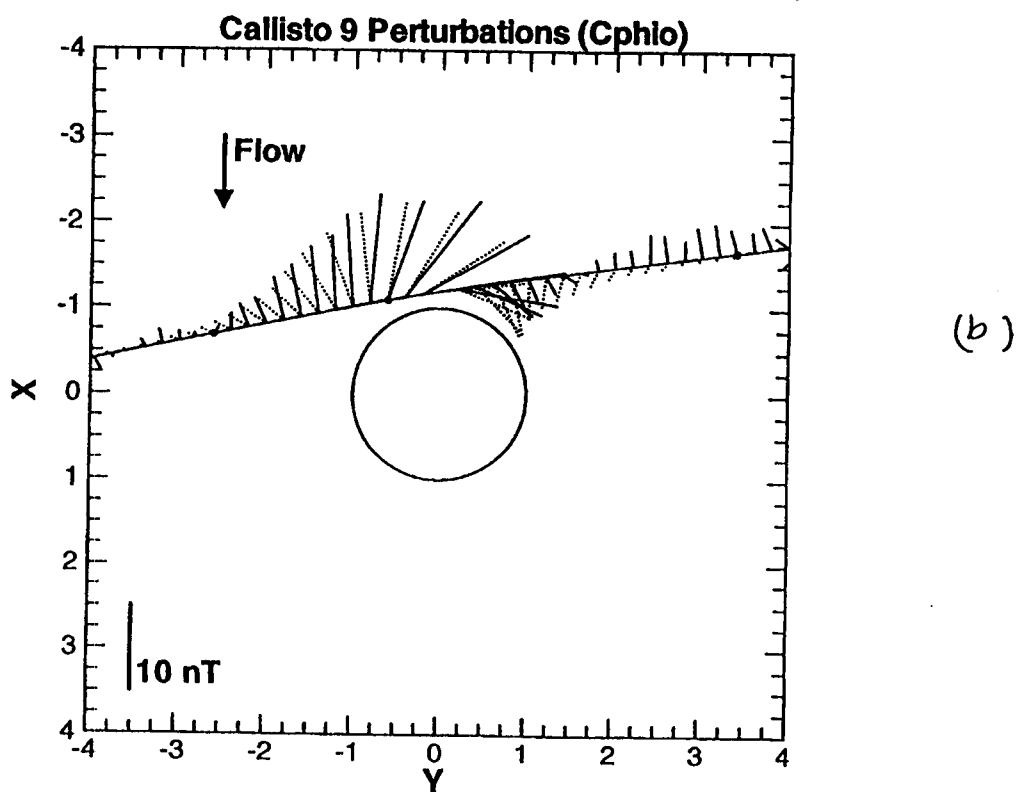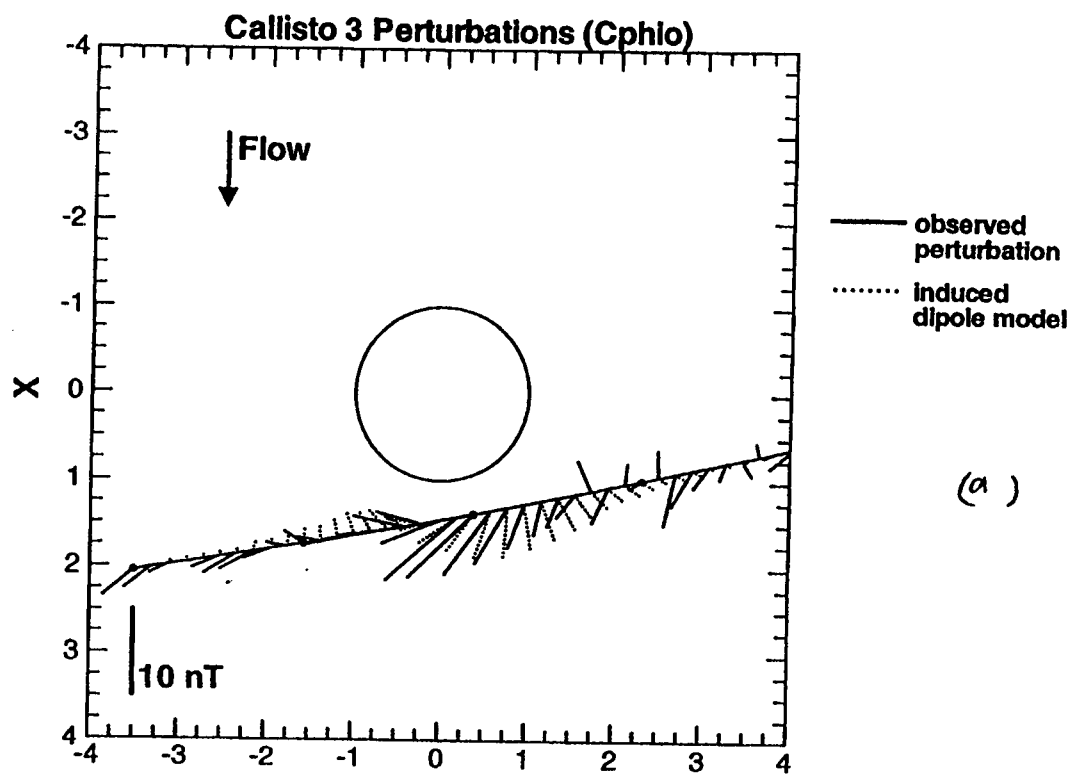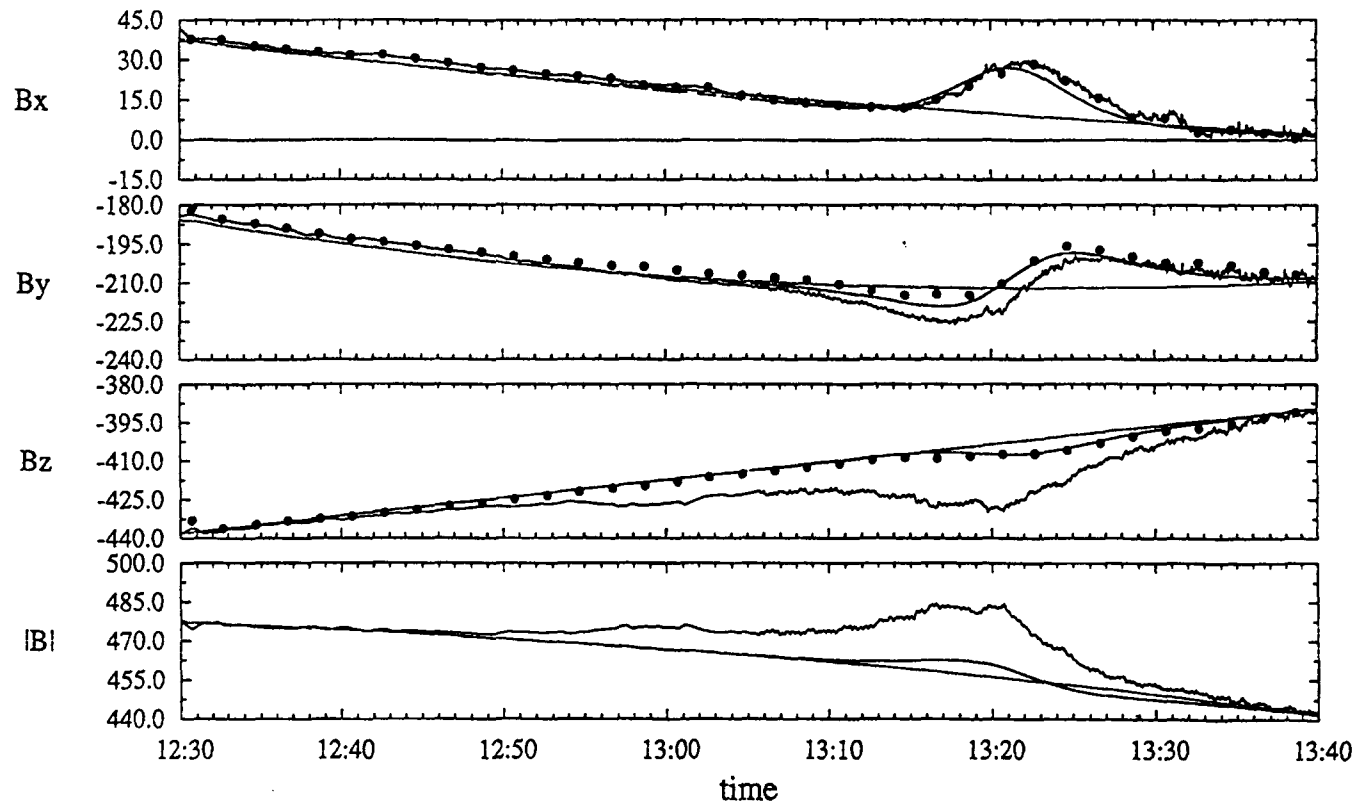
Jovian Background Field at Europa

(a)

E4

E14

Jovian Background Field at Callisto

(b)

C9

C3

Figure 1

Callisto 3 Perturbations (Cphio)

Callisto 9 Perturbations (Cphio)

Figure 3

Figure 2

X	-9.84	-8.17	-6.56	-4.95	-3.31	-1.65	0.04	1.75
Y	8.06	6.16	4.34	2.51	0.67	-1.16	-2.96	-4.72
Z	0.28	0.31	0.34	0.37	0.39	0.41	0.42	0.43
R	12.72	10.24	7.87	5.56	3.40	2.06	2.99	5.05

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